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Effect of Broad-banding Amplifiers on E-field Probe Measurements in a Reverberant Cavity

Timothy S. Priest

DSTO-RR-0227

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ABSTRACT

Broad-band electric-field probes have gained wide-spread acceptance for use in reverberation chambers in recent years, primarily due to their ease of use. However, recent work with AOD has highlighted situations where E-field probes may return ambiguous results. In particular, the stirring ratio may be greatly affected by the wide-band frequency reception of an E-field probe when in the presence of multiple frequencies in a reverberant environment

Monte Carlo simulations conducted to examine the effects of measuring multiple frequencies in a reverberant cavity were compared with experimental data that was taken by an E-field probe that measured the E-field generated by an antenna driven by an amplifier exhibiting distortion in a reverberation chamber. The experimental results indicate that considerable care should be taken to ensure frequency purity in a reverberant environment when making E-field probe measurements.

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Executive Summary

DSTO currently operates an experimental electromagnetic reverberation chamber and conducts feasibility research into the use of this technology to perform indigenous whole-aircraft testing.

As part of the research program, an extensive field-mapping exercise was undertaken in 2000. Analysis of results from that study showed a low stirring ratio (SR) across the entire 2.5-7.5 GHz frequency range of the AR200T2G8 power amplifier being used.

Here we propose a hypothesis that amplifier distortion caused independent excitation of different cavity-modes in the reverberation chamber which, coupled with the broad-band nature of E-field probes, caused the SR to deviate significantly from its expected value.

Monte Carlo analysis of multiple frequencies in a reverberant environment shows encouraging agreement with experimental results, which seems to confirm this hypothesis. This result has significant impact for the entire electromagnetic compatibility community and indicates that considerable care should be taken to ensure frequency purity in a reverberant environment when making E-field probe measurements.

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The author obtained a B.Sc.(Hons) in Physics from the University of New England in 1993. The author spent a 12 month secondment at the University of Kent, Canterbury working on his Ph.D. into 'Low-coherence optical fibre sensing of electric field and charge' before returning to Australia to complete his Ph.D. He has been with the DSTO since September 1998.

Contents

1. Introduction

Broad-band electric-field probes have gained wide-spread acceptance for use in reverberation chambers in recent years, primarily due to their ease of use. However, in situations where more than one frequency is present in a reverberant environment probes may return ambiguous results. In particular, the SR may be greatly affected by the wide-band frequency reception of an E-field probe when in the presence of multiple frequencies in a reverberant environment; even if the secondary frequencies are of significantly lower power (more than 25 dB down) than the primary frequency.

Monte Carlo simulations conducted to examine the effects of multiple frequencies on probe measurements in a reverberant cavity were compared with experimental data that was taken by an E-field probe[1] in a reverberation chamber. The experimental results show good agreement with the simulation and show that considerable care needs to be taken to ensure frequency purity in a reverberant environment when making E-field probe measurements.

2. Background

Experiments in DSTO's large electromagnetic reverberation chamber, conducted in January 2001, showed a low SR across the entire 2.5-7.5 GHz frequency range of the AR200T2G8 power amplifier that was being used as an RF power source [1]. A comprehensive check of equipment and software showed that the power amplifier was exhibiting significant modulation distortion [2]; displaying secondary frequency amplitudes approximately 30 dB down on that of the primary frequency. We present here an hypothesis that this distortion caused independent excitation of different cavity-modes in the reverberation chamber [3]. In turn, the non-discriminant nature of the E-field probes resulted in the weighted-average of all cavity-modes present in the chamber being measured [4]. The combination of the weighted-averaging and multiple frequencies present in the reverberant cavity caused the SR to deviate significantly from its expected value.

Monte Carlo simulation [5] was selected to test the hypothesis due to the statistical nature of the E-field present in reverberant cavities. The method of simulation is detailed in the following section.

1. Where the power amplifier supplying the E-field to the chamber was exhibiting appreciable modulation distortion.

3. Simulation

3.1 Simulation Definition

As stated in Section 2, the Monte Carlo technique of probe measurements in a reverberant environment (in the presence of multiple frequencies) was conducted. In order to minimise the simulation time several assumptions were made:

1. the secondary frequencies (Figure 1) of the amplifier being far-enough removed from the primary frequency that they excited different cavity-modes in the chamber,
2. the modal-density [6] in the reverberant cavity is large enough that incrementing the stirrer by one position gives statistically independent sampling, and
3. that the probe would linearly measure the contributions to the field (arising from the primary frequency and secondary frequencies).

The validity of the above assumptions will vary depending on the frequency under consideration, the chamber size and construction materials [7] and the offset of the secondary frequencies from the primary frequency. In the case of the large DSTO chamber, at the frequencies under investigation and with the level of side-banding being displayed, all of the assumptions were considered reasonable [8].

Assumption 1 is central to the argument, since no perceivable effect would be seen in the probe measurements unless this assumption held. Likewise, it is reasonable to assume that the probe will act in a linear manner when summing the contributions from different frequencies (assumption 3). There was also sufficient evidence, both experimental [7], [1] and theoretical [6], [9], to support the assumption that the experimental data was independent (assumption 2).

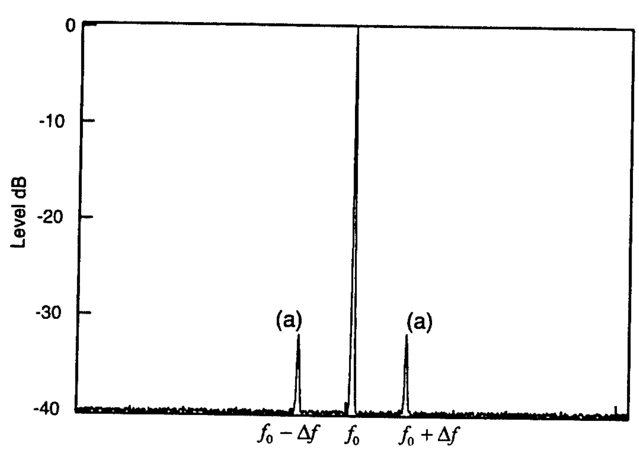

Figure 1: Frequency source exhibiting secondary frequency excitation (a).

While E-field probes measure electric field, historically the results from reverberation chambers are reported in terms of power ($\propto E^2$) since most early measurements were made with antennas. In order to make comparisons easy, in the present work we convert the simulated E-field (chi distributed) to power (chi-squared distributed) before comparison; this in no way effects the validity of the results and is done only to make comparison with standard values easier. For this reason, we will refer to chi-squared χ^2 data exclusively in the results section of this report.

The simulation was carried out as follows[2]:

a) three separate 2-degrees-of-freedom chi distributed (χ_2) data[3], each having N independent points, were sampled. One distribution represented the field attributable to the primary frequency f_0 while the other two distributions represented the contributions made to the total field by the secondary amplifier excitation, at the frequencies $f_0 \pm \Delta f$,

b) a fractional weighting W_x was given to each of the distributions,

c) a composite distribution was calculated using the weighted-average of the three separate distributions for each of the N points in the distributions, as given below:

$$CD(N, W) = \sum_{n=1}^{N} \sum_{x=1}^{3} W_{x\,x}\chi_2(n) \qquad (1)$$

where CD is the composite distribution, W_x is the weighting given to each of the distributions and ${}_x\chi_2(n)$ is the value of the x'th chi distributed data at the point n (of the N possible points),

d) the individual components of the composite function $CD(N, W)$ were squared, giving chi-squared distributed results $CD^2(N, W)$. As mentioned above, this allowed easier interpretation of the results with conventional test parameters,

e) the Stirring Ratio (SR), Normalised Standard Deviation (NSD) and Peak-to-Average Ratio (PAR) were calculated for both the ${}_2\chi_2^2(n)$ distribution (corresponding to the squared field distribution resulting from the primary frequency alone), and the composite distribution $CD^2(N, W)$. The results were stored in separate arrays of length N,

f) steps (a)-(d) were repeated for 10000 iterations. The SR, NSD and PAR being averaged to give the mean value for each over the 10000 iterations,

g) steps (a)-(e) were repeated for varying values of N, ranging from 3-2000.

The SR, NSD and PAR values obtained from the composite distribution were compared to the nominal values obtained from the ${}_2\chi_2^2(n)$ distribution [10] to give the relative

2. For the PDF step (f) was not carried out. Instead an indicative number of N=180 was used.

3. The probability density for the chi probability density function with 2 degrees-of-freedom is:

$$f(x) = e^{\frac{-x}{2}}/(2\Gamma(1)), \text{ where } \Gamma(1) = \int_0^{\infty} e^{-s}ds \text{ is the gamma distribution.}$$

change to the relevant value (SR, NSD and PAR). In the case of the PDF, and the associated cumulative distribution function (CDF), the expected (unperturbed) PDF and CDF distributions were compared directly with those obtained with amplifier distortion present.

3.2 Simulation Results

The majority of the data falls in the region surrounding the average value in a chi-squared distribution, as can be seen in Figure 2. Nevertheless, a small number of points have values considerably smaller (or larger) than the average (Figure 2). Furthermore, the asymmetry (skewedness) of the chi-squared function means that there is a higher probability of obtaining a value considerably smaller than the average than there is of obtaining a value considerably larger than the average (Figure 3).

The weighted-averaging due to the probe acts as a smoothing function [4], resulting in data that vary greatly from the average being most significantly affected by the averaging. The result of this weighted-averaging on χ_2^2 data can clearly be seen in Figure 4, where any deep nulls (very low values) in the χ_2^2 data have been significantly normalised towards the mean by the weighted averaging. To understand why this occurs, consider the case where an amplifier is exhibiting secondary frequency excitations (Figure 1), each of which may give rise to independent chi-squared distributions in a reverberant environment. The probability of a null in the primary frequency distribution being averaged with a much higher value from at least one of the two side-lobe distributions is high. This results in a reading that is much larger than the unperturbed primary frequency distribution would give alone. Since the nulls in a chi-squared distribution may be >25 dB lower than the average value, even secondary frequencies with amplitudes 20 dB smaller than that of the primary frequency may cause significant distortion in the weighted-average value measured by an E-field probe, as evidenced in Figure 4.

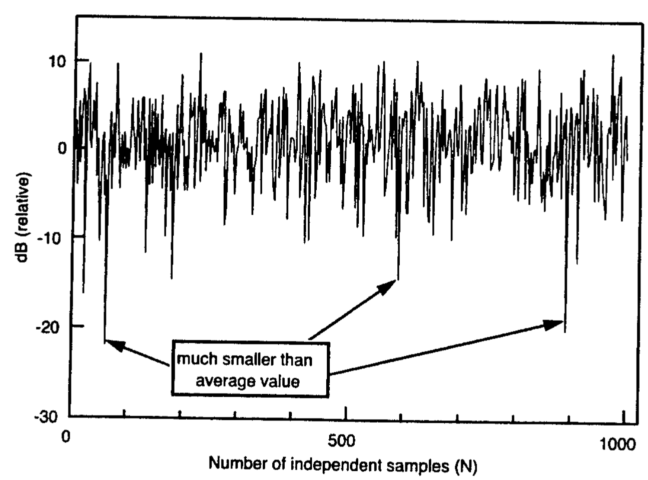

Figure 2: Chi sampled data, showing the small number of samples that vary greatly from the mean.

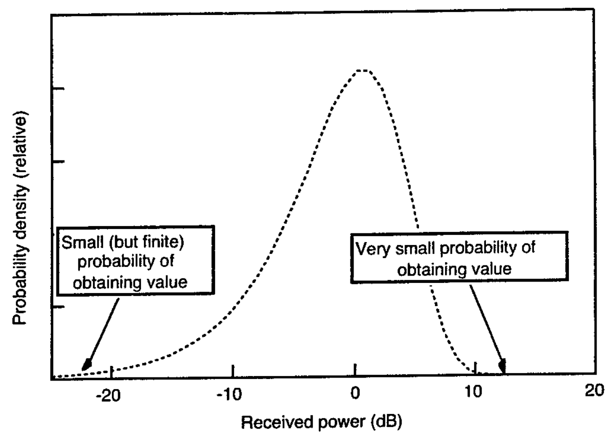

Figure 3: Typical probability density function for sampled data that are χ_2 distributed.

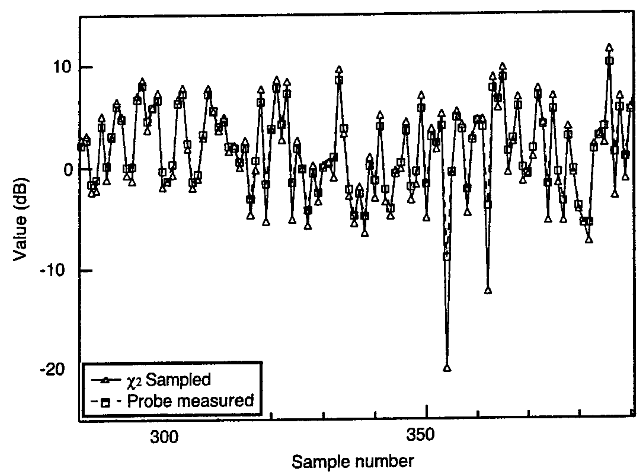

Figure 4: The effect of weighted-averaging on chi sampled data.

The results of the simulation on the SR, NSD and PAR are shown in Figures 5 to 9. Figure 5 shows the depression (in dB) of the composite function's SR as a function of the number of independent samples as the amplitude of the secondary frequencies was increased from 20 dB below the primary frequency to 10 dB below than the primary frequency. The depression in the SR was found to increase as the number of independent samples increased; a result of the increasing probability of encountering a minimum in the chi-squared distribution with larger sample numbers.

Figure 6 shows the effect on the NSD (as a ratio to the chi-distributed NSD) as the amplitude of the secondary frequencies was increased. Notice that the effect of amplifier distortion on the NSD is significantly less than the effect on the SR. This is reasonable to expect since, in general, the NSD is less influenced by small numbers of points having

large-scale fluctuations from the mean than is the SR. Nevertheless, for extreme distortion the NSD does exhibit appreciable depression.

It is also interesting to note that the number of independent samples measured by the probe has considerably less effect on the NSD than it does on the SR. This is explained by:

1. only the data that diverge greatly from the mean are significantly affected by the weighted-averaging process (and, statistically, there are few of these), and
2. the standard deviation is inherently insensitive to small amounts of data "straying" from the mean.

Figure 7 demonstrates the expected modification to the PAR induced by a distorting amplifier source when compared to the PAR measured from the unperturbed chi-squared distribution as the secondary frequency amplitude was again increased from 20 dB below the primary frequency to 10 dB below. Like the NSD, the PAR is less susceptible to the effects caused by distorting amplifiers than is the SR, but does exhibit a degree of depression for larger amounts of amplifier distortion. Again, this is to be expected, since the effect weighted-averaging has on the maximum values of the chi-squared distribution will be significantly less than the effect it has on the minimum values of the same distribution.

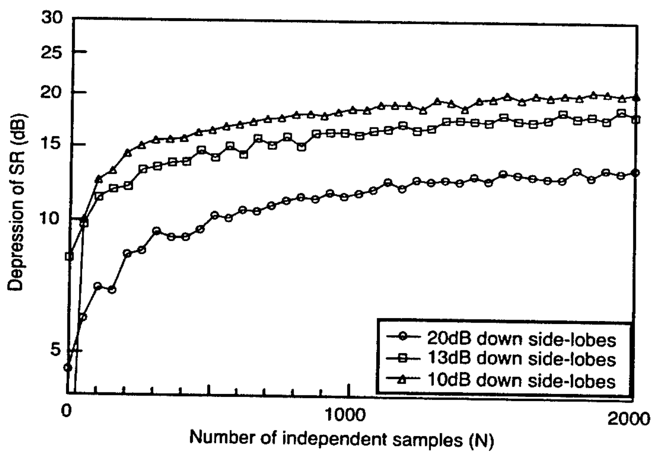

Figure 5: Depression of SR as a function of sample size for several values of amplifier distortion.

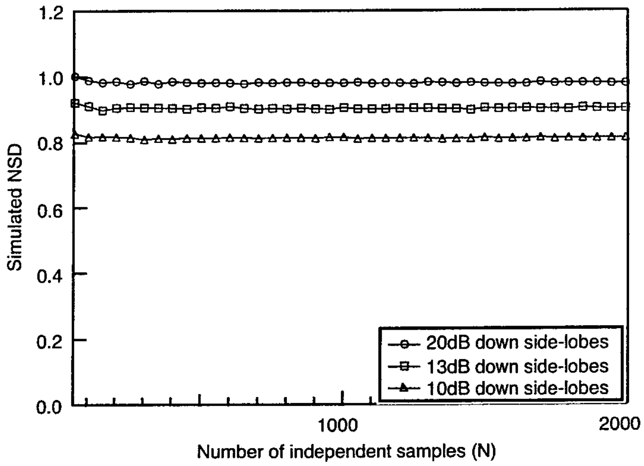

Figure 6: Depression of NSD as a function of sample size for several values of amplifier distortion.

Figure 8 shows the perturbation to the PDF as distortion of the source was increased. The expected "narrowing", and subsequent decrease in asymmetry, of the PDF is clearly evident, even for moderate amounts of amplifier distortion. Similarly, Figure 9 illustrates how the CDF is influenced by the amplifier distortion in a reverberant cavity. The CDF reflects the perturbations seen in the PDF. In particular, there is a general increase in the maximum slope of the CDF, causing it to diverge considerably from the expected chi-squared behaviour of the data. Even small amounts of amplifier distortion will significantly affect the chi-squaredness of the data, with the degree of divergence depending on the level of distortion. Such discrepancies could easily be mistaken as being indicative of poor chamber performance.

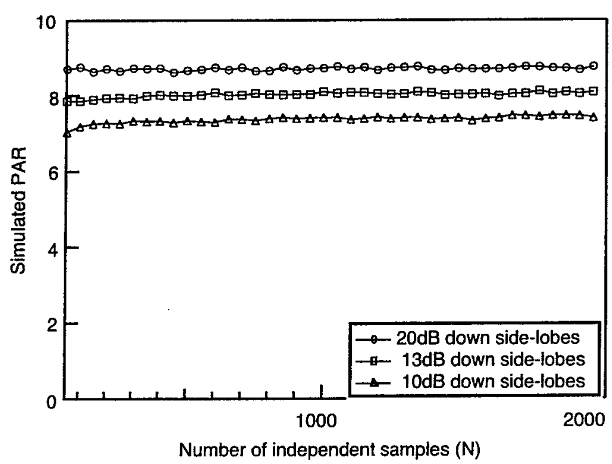

Figure 7: Depression of PAR as a function of sample size for several values of amplifier distortion.

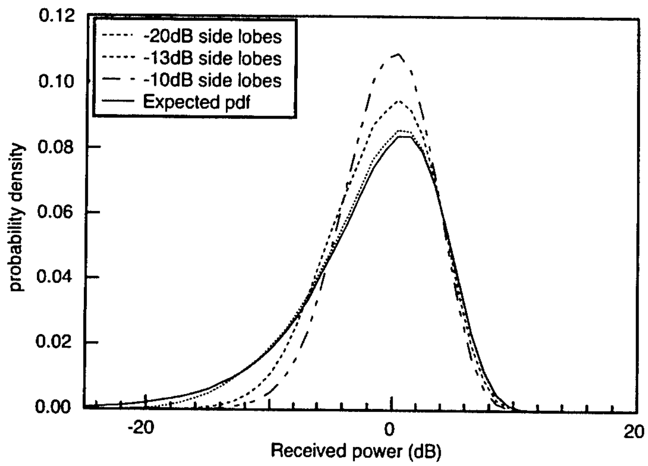

Figure 8: Probability density function for different values of amplifier distortion as measured by an E-field probe.

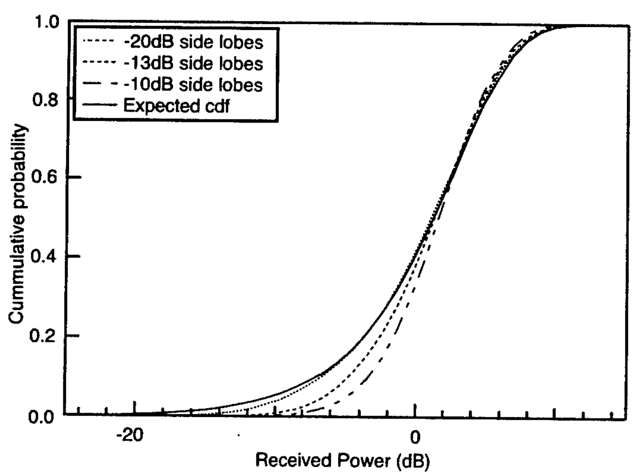

Figure 9: Cumulative distribution function for different values of amplifier distortion as measured by an E-field probe.

4. Comparison with real data

Motivation for the current study arose from observations of seemingly aberrant behaviour of the SR in DSTO's large reverberation chamber [1], where the SR was found to be depressed by more than 10dB over an extended frequency range.

Table 1 lists the SR values found for the full frequency range under test in the DSTO chamber when the problem was first detected. The depression in the SR can be seen for the frequency range 2.5-7.5GHz. There is a depression of some 11-12dB shown in the 2.5-7.5GHz range, assuming the SR for the frequency ranges both above 7.5GHz and below 2.5GHz are indicative of the true SR.

If this depression is cross-referenced against the simulated depression of SR (Figure 5) for the number of independent samples (N=180), an expected side-lobe power of approximately 13dB below the primary frequency power is obtained. Using this relative power (-13dB) (and with reference to Figures 6 and 7) we can predict the effect on the NSD and PAR. Using this method, the NSD and PAR were found to be 0.91 and 8.1 respectively; a reasonable match to the experimentally obtained values, as shown in Table 2.

Table 1: Comparison of stirring ratios

Frequency Range (GHz)	Average Value of SR over range (dB)
1-2.5	32
2.5-7.5*	21
7.5-18	33
* Amplifier exhibiting distortion	

Table 2: Comparison of NSD and PAR with simulated results

Parameter	Frequency Range (GHz)	Simulation (-13 dB secondary frequency)	Average Value (experimental)
NSD	1-2.5		1.01
	2.5-7.5*	0.91	0.93
	7.5-18		1.00
PAR (dB)	1-2.5		8.9
	2.5-7.5*	8.1	8.2
	7.5-18		8.8
* Amplifier exhibiting distortion			

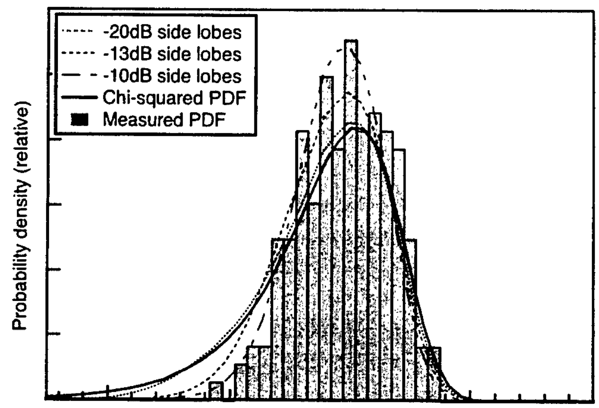

Figure 10: Experimental probability density function (PDF) compared with the simulated values.

The PDF obtained experimentally was also compared with the PDF derived from the simulation. The result is shown in Figure 10. Again, there is generally good correlation between the simulation and experimental results. In particular the reduction in asymmetry of the PDF and the associated increase in the peak-density is clearly evident.[4]

The particular experimental trace shown here exhibits characteristics of having had larger amounts of amplifier distortion present than the -13 dB average shown in Table 1. Indeed, the experimentally measured depression of the SR for this particular sample was 14 dB, indicating (from Figure 5) a "side-band" amplitude of approximately 10 dB below the primary-frequency amplitude. This correlates with Figure 10.

Figure 10 compares the experimentally obtained CDF with the simulated CDFs obtained for different amounts of amplifier distortion. The results for the CDF comparison align closely with the conclusions found from the PDF[5]; namely, that this particular set of data resembles one in which the "side-band" amplitude of the amplifier was -10.5 dB.

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4. The noise present in the experimental PDF should not be taken as depicting poor data. Rather, this is typical of the PDF that can be expected from data having a sample-space of only 180 points.

5. This is as expected, since the CDF and PDF are only different representations of the same sample of data.

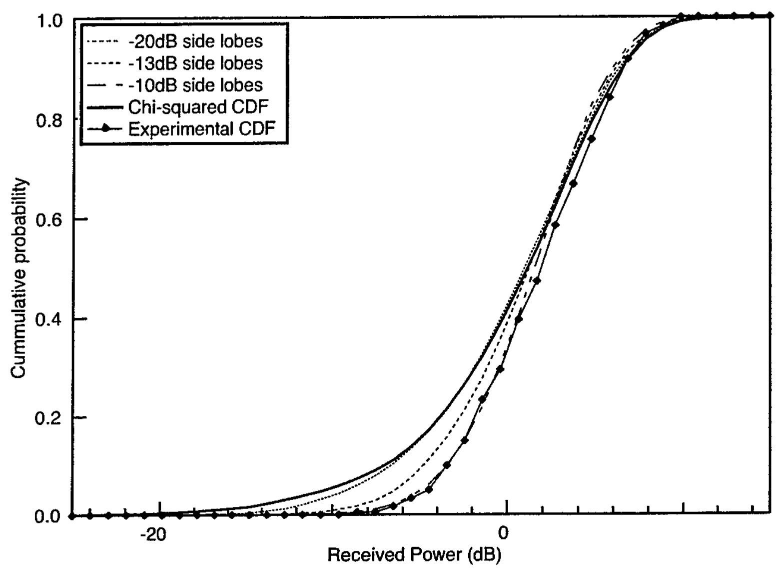

Figure 11: Experimental cumulative distribution function (CDF) compared with the simulated values.

5. Complications

Figure 11 shows the actual frequency-output response from the distorting amplifier, for a central frequency of 5.0GHz. While the expected secondary frequencies are clearly evident, their maximum amplitude is significantly smaller (32 dB down) than expected. The frequency response of the amplifier is also rather more complicated than depicted in Figure 1, and modelled in this text.

The small amplitude of the secondary frequencies, when compared with the measured depression in the SR, is perplexing. For instance, according to the modelling calculations, and comparisons with the experimental data, the side-lobe amplitude should have been in the order of 10 dB below the primary-frequency; not the 32 dB below evident in Figure 12.

The complicated nature of the amplifier distortion may help to explain the significant differences in the calculated and observed depression in the SR, NSD and PAR. In particular, the width of the secondary frequencies suggests that multiple cavity-modes may have been excited by the distorting amplifier. If multiple cavity-modes were excited then the signal returned from the E-field probe would be the superposition of the individual responses. While this was not modelled in the present work, an estimate of the effect on the SR can be made as follows.

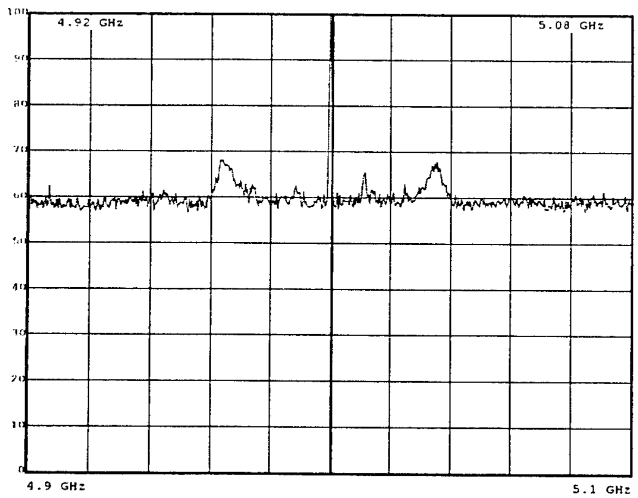

Figure 12: Frequency response of the distorting amplifier.

The probability of obtaining an "average" power reading from each independent cavity-mode is much greater than the probability of obtaining a very small (or very large) reading. We can therefore make the assumption that when a specific independent mode returns a deep null, there is a large probability that the other independent modes will return readings that are close to the average. This means we can superpose the independent cavity-modes. From this superposition we can obtain an "order-of-magnitude" calculation of the expected "equivalent" single side-lobe amplitude.

From Figure 12, and assuming an average modal-spacing (η_m) of 21kHz[6], we can obtain the approximate single-mode amplitude (A_{single}) from

$$A_{single} = \sum_m \frac{1}{2} \times \frac{(width_m)}{\eta_m} \times (Amax_m - Amin_m) \qquad (2)$$

where $width_m$ is the width of the m'th side-lobe, $Amax_m$ and $Amin_m$ are the maximum and minimum amplitudes of the distorting amplifier's secondary frequencies respectively and the sum is taken over all secondary frequencies present.

Substituting the relevant values into equation 2 gives $A_{single} \cong -8dB$, which is reasonably close to the expected value of -10 dB. This lends credence to the theory of multiple cavity-mode excitation.

While the above hypothesis seems reasonable, it should be noted that no rigorous modelling of the system has, as yet, been undertaken and so the conjecture should be used with some caution at this time.

Whatever the reason, the amount of depression exhibited by the SR for the relatively small maximum amplitude of the amplifier distortion is disturbing. It indicates that the

6. The theoretical modal spacing for a rectangular cavity at 5GHz is approximately 21kHz assuming the quality factor of the chamber is neglected.

presence of multiple frequencies in a reverberant cavity may affect the measurements of E-field probes even more than first hypothesised. More detailed analysis to quantify this phenomenon is presently being undertaken.

6. Conclusions

While E-field probes offer advantages in terms of ease of use, they must be used with some caution in a reverberant cavity. Their inherent wide-band nature means that all frequencies present in the cavity (and within the bandwidth of the probe) will be measured by the probe. As a result, the field measured by an E-field probe will be the weighted-average of all frequencies present. Combined with the chi-squared nature of the field in a reverberant cavity, this may provide potentially misleading results.

A Monte Carlo simulation, was conducted to study the effects of multiple frequencies on probe measurements in a reverberant cavity. The results of the simulation predict deviations of all the major chamber quality factors (SR, NSD, PAR and PDF) when the E-field in a cavity containing multiple frequencies is measured by a probe. In particular, the stirring ratio is particularly sensitive to the presence of multiple frequencies and may be depressed by as much as 10 dB, even when the power of the secondary frequency is more than 20 dB below that of the primary frequency.

The results found in the simulation compare reasonably well with experimental results obtained in the large DSTO reverberation chamber, where a malfunctioning power amplifier was exhibiting secondary frequency emission.

The experimental results obtained also indicate that the effect of multiple cavity excitations may be even stronger than first thought, with each independent cavity-mode excitation adding to the overall perturbation of the data. As a result, even secondary emissions at levels more than 30 dB down on the primary frequency may cause significant disturbances to the measured field.

As discussed in the text, the presence of multiple frequencies in a reverberant environment also manifests as a large decrease in the SR; even for small amounts of distortion. This makes the SR a particularly sensitive measure of any multiple-frequency activity occurring in a reverberant environment. In light of this, the author believes that recent moves to exclude the SR from the characteristic measures of chamber performance should be reconsidered by the reverberation chamber community.

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19. ABSTRACT

Broad-band electric-field probes have gained wide-spread acceptance for use in reverberation chambers in recent years, primarily due to their ease of use. However, recent work with AOD has highlighted situations where E-field probes may return ambiguous results. In particular, the SR may be greatly affected by the wide-band frequency reception of an e-field probe when in the presence of multiple frequencies in a reverberant environment

Monté-carlo simulations conducted to examine the effects of multiple frequencies on probe measurements in a reverberant cavity were compared with experimental data that was taken by an E-field probe that was in the presence of an amplifier exhibiting distortion in a reverberation chamber. The experimental results indicate that considerable care should be taken to ensure frequency purity in a reverberant environment when making e-field probe measurements.